Electrosurgery

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accomplished using either monopolar or bipolar electrodes. In bipolar applications, both the current source and current sink electrodes are located at the surgical site. A typical bipolar electrode might consist of forceps with the tongs connected to the active terminals of the generator. In both cutting and coagulating processes, whether monopolar or bipolar electrodes are used, a layer of charred tissue condenses on the cool electrode which must be removed periodically.

The histologic effects of cutting current are varied and apparently depend on technique. In experiments on the histologic effects of electrosurgery different results have been obtained by Kelly and Ward [1], Knecht *et al* [10], Oringer [6] and others. Knecht *et al* [10] found that the healing process in an electrosurgical incision was slightly slower than that for incisions made by a cold scalpel. This is probably due to the slightly deeper penetration of cell damage in the study and is reflected in wound strength studies. In this study the wound strength of an electrosurgical cut was less than that of a cold scalpel cut until about 21 days after surgery. After 21 days, no difference in wound strength was measurable. Ward [1] found that an electrosurgical cut generally forms slightly more scar tissue on healing than a cold scalpel cut if the closure of the two wounds was identical. The cellular layers within about 0.1 mm of the scalpel electrode showed electrodessication effects when sine wave cutting was used. In a later series of studies on tissues of the oral cavity, Oringer observed that when the cutting current was carefully controlled, the damage was confined to the cut cellular layer and the layer of cells adjacent to the cut was undamaged [6, 7]. The cell destruction was apparently self-limiting to the extent that no damage to the cytoplasm or cell nucleus of the cut layer was visible in light or electron micrographs [6]. Oringer describes the margin of an excised squamous cell carcinoma which had been removed by electrosurgery [6]. Under the electron microscope, at a magnification of 47 400, the margin was seen to contain several clear examples of cells sheared in half with no damage to the remainder. Oringer and others observed faster healing with less scar tissue in the electrosurgical incision. The variety of results obtained is probably due to differences in waveform, surgical technique, tissue characteristics and scalpel electrodes used in the studies.

When combined sine wave and interrupted (coagulating) waveforms, or spark gap sources are used for cutting, a coagulum layer extends deeper into the tissues under the dessicated layer [1]. The histology and healing characteristics more closely resemble those of coagulated tissue.

Coagulation techniques include: (1) fulguration – also called spray coagulation or black coagulation – in which the tissue is carbonized by arc strikes, (2) dessication, in which the cells are dehydrated resulting in considerable shrinking, and (3) white coagulation, in which the tissue is more slowly cooked to a coagulum. In fulguration* techniques, the active

* *Fulgur* is the latin noun for lightning, while *fulguratus* is the present participle of *fulgurare*, to flash.

because coagulation, like other forms of thermal damage, follows an Arrhenius relationship in which the tissue damage depends linearly on the time of exposure and exponentially on the temperature [9]. Consequently, the damage resulting from elevated tissue temperatures is calculated by evaluating a damage integral which utilizes the temperature history to accumulate the total tissue damage. An example Arrhenius function for damage accumulation is shown in Equation 4.3.

$$\Omega = \int A \exp(-E_a/RT)\, dt \tag{4.3}$$

Where Ω = accumulated damage (dimensionless)
A = 'frequency factor' (1/s)
E_a = activation energy (J)
R = universal gas-constant (J/K)
T = temperature (K)
t = time (s)

The above relationship will be used in a subsequent discussion of cutting methods and is presented here as an introduction to the basic physical process. The damage integral approach applies equally well to both cutting and coagulating. Before leaving the discussion of coagulation, it is of interest to note that many different techniques have been used to seal several vessels. For example, vessel coagulation is also readily obtained by grasping the vessel with a hemostat or forceps and applying a monopolar active electrode to the instrument. Alternatively, the vessel may be gently stroked with the flat surface of a scalpel electrode kept in constant contact. An arc is not required to obtain coagulation, but may accompany the application of surgical power even when bipolar electrodes are used.

4.2.2 Arcs and arc formation

White coagulation is accomplished without an arc at the active electrode. Spray coagulation, also called black coagulation or fulguration, utilizes a very intense arc. In this technique a charred black mass results from the arcing to tissue. The method is faster than white coagulation, but is no more effective and results in far more tissue destruction than white coagulation [7]. There are some situations for which it is preferable to white coagulation. On the other hand, an arc is absolutely essential for effective cutting of tissues. Since arcs have interesting properties this section discusses the heat transfer and physical characteristics of arcs while the remainder of the chapter deals with their effects on electrosurgical generators and on other electronic instruments in the operating theater.

Since the arc is so important to surgical cutting, it is appropriate to take a closer look at how it is formed and what causes it to collapse. As briefly described in Chapter 3 an arc is formed when the electric field between two

electrodes separated (in the surgical case) by a gaseous medium becomes strong enough to ionize or break down the gas. When that happens the gas constituent molecules are excited to high energy states and dissociate, forming ions which are charge-carrying. The ions are then accelerated by the strong electric field and collide with uncharged gas molecules. If the electric field is strong enough, the accelerated ions will have enough energy to ionize the gas molecule on collision. This process is illustrated in Fig. 4.5, in which a hypothetical gas dissociates to form a positive and negative ion. The ions

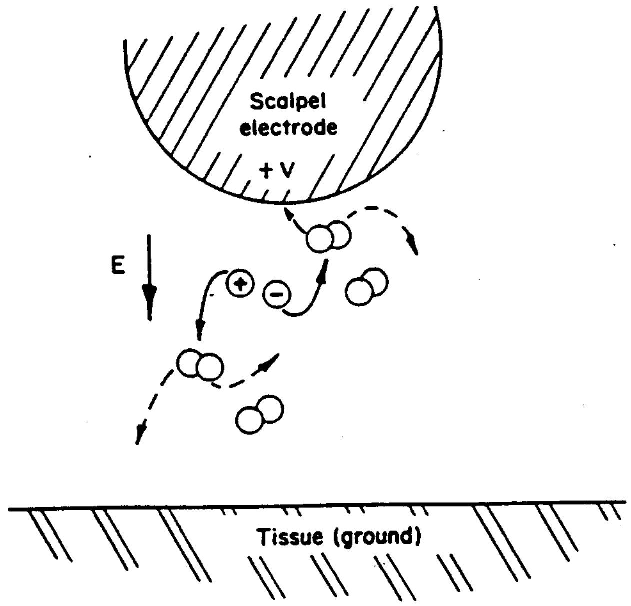

Fig. 4.5 Imagining the scalpel electrode to be a cylindrical cutting wire at high voltage (the positive half-cycle is shown) above a ground plane; ions form and are accelerated by the electric field (E) striking other molecules and forming more ions.

are accelerated by the electric field according to Coulomb's force law (see Appendix A, Equation A1). The positive ion is repelled from the source terminal (+V) on its positive half-cycle and the negative ion is attracted to it. Both ions collide with other uncharged molecules after a short distance. If the ion has enough momentum when it collides with the molecule it will force a dissociation, potentially creating four ions which will in turn be accelerated. This process is referred to as avalanche multiplication. Strong electric fields are required since the mean free path between collisions is of the order of 100 Å, and the acceleration must be large enough to sustain the avalanche multiplication effect which causes the ion population to grow. In weak electric fields where there is not enough acceleration the ion cloud collapses due to an insufficient ion generation rate. As the ion population approaches a critical density the equivalent impedance between the electrode and the tissue drops to a low value. Current flows, and the plasma

cloud formed by the excited ionized atoms gives off light as some of the ions relax to lower energy states. If the electric field between the electrodes falls below the minimum required to sustain the plasma cloud – since the plasma is conductive, that is if the current falls below the holding current – then the plasma quickly collapses and the arc is quenched. An arc may be re-established when the field again exceeds the breakdown field. Note that, as in the case of the spark gap generator, the arc may be established on either the positive or negative half-cycle of the sine wave. On the negative half-cycle the positive ions will be accelerated toward the scalpel electrode in Fig. 4.5 and the negative ions repelled. So when a stable surgical arc exists, it forms and is quenched on each half-cycle of the waveform – of the order of once every microsecond for 500 kHz machines and once in about 430 nanoseconds for 2.3 MHz machines. The different arc durations and frequency of establishment may give rise to the slightly different cutting characteristics of the two frequencies which have been claimed by users.

The arc dominates the series impedances which make up the tissue equivalent circuit since most of the available generator power (in terms of the output voltage) is required to establish the arc. Of course, it is perhaps questionable to describe the arc in time-averaged a.c. analysis terms such as 'effective impedance' since the arc is of shorter duration than one of the wave half-cycles. However, it does make considerable descriptive sense even if it is not strictly valid terminology.

The arc also has an extensive effect on the frequency spectrum of the generator (as will be shown in some detail), contributes energy to the voltage and current spectra of the generator and is the origin of the most difficult to extricate noise signal components. The bulk of the interference observed on electrophysiologic monitors has its roots in the cutting/ coagulating arc.

4.2.3 Arcs in cutting processes, phenomena

Several investigations have revealed some of the features which separate cutting action from coagulation. Cutting action requires that tissue cellular layers be separated or disrupted with minimal damage to adjacent cells. In coagulation the goal is for the damage contour to penetrate adjacent cell layers in order to assure closure of seeping vessels or other tissue. Honig [1] discussed the mechanism of cutting with loop electrodes of small diameter wire. His theoretical analysis assumed that there was no arc between the loop and the adjacent tissue. He was able to show that adequate local power density was available to vaporize the cellular layers in immediate contact with the cutting loop and that cells a few millimeters away from the loop would have very modest temperature rises. Although this analysis is considerably simplified over the actual clinical case – which was necessary to make the problem solvable – the results are extremely illuminating. The

essential component of effective cutting is that the power density be highly concentrated in a very small region to obtain tissue disruption with shallow penetration of destruction. In the small wire loop electrode case, for no arc at the tissue, the power density drops off as the reciprocal of the radius squares. This is because the small wire may be thought of as a line source of current (as shown in Fig. 4.6) and the electric field (see Appendix B for details) is given by:

$$\mathbf{E} = \frac{I}{2\pi\sigma L r}\mathbf{a}_r = \frac{\mathrm{K}}{r}\mathbf{a}_r \tag{4.4}$$

Where $\mathbf{E}$ = electric field strength (V/m)
I = total current applied to the wire (A)
σ = electrical conductivity of the medium (S/m)
L = length of the wire in contact with the tissues (m)
r = radius of the point at which $\mathbf{E}$ is found from the center of the wire (m)
K = a convenient descriptive constant, as used by Honig [1]
$\mathbf{a}_r$ = the unit vector in the radial direction

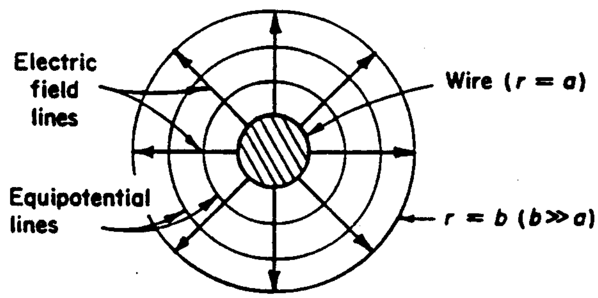

Fig. 4.6 Electric field lines and equipotential surfaces near a wire electrode of radius a immersed in an infinite medium where the other electrode is assumed to be a cylinder of large radius, b, as used by Honig [1].

The power density at any point in a conductive medium at moderate frequencies (less than about 40 MHz in tissues) is given by the vector dot product of the **E** field and **J** field vectors (see Appendix A for the development of this). So, from the above result the power density is given by:

$$P = \frac{\mathrm{K}^2}{\sigma r^2} \tag{4.5}$$

Where P = volumetric power density (W/m^3)
K = as defined in Equation 4.4
σ = medium electrical conductivity (S/m)

Honig's observations suggest that the more confined the current can be made the more effective the cutting action will be. Vogler and Mylrea [3] have also studied cutting processes. They, like Honig, hold that electrical conduction current heats the tissue up to boiling temperature and the cells are basically exploded by the phase change due to boiling. Both of these explanations are plausible and consistent with the observation that steam is nearly always observed during cutting. Also, since the cellular volume is so small, it would not require much water vaporization to burst a cell.

There is another mechanism which operates in parallel with the boiling and vaporization mechanism to disrupt the cells. Recent measurements by Bonney *et al.* [9] and calculations by Papa and Sethuraman [10] show that when an intense electromagnetic field impinges on absorbing tissue an acoustic wave is generated by the thermoelastic properties of the tissue. The origin of the pressure wave lies in the inability of the tissue (or any other material for that matter) to maintain thermodynamic equilibrium when rapidly heated. That is the power deposition in the tissue is so intense that the maximum rate of vapor formation (i.e. the nucleation of vapor bubbles from super-heated liquid) is not fast enough to maintain equilibrium. As a result the tissue pressure rapidly increases in a local region around the arc site. The local pressure increases may be intense enough to cause tissue ablation and also propagate as acoustic waves. Although their calculations and measurements were carried out for laser impulses, the essential feature required of the power deposition to generate acoustic waves is that it must be fast enough to raise the tissue temperature in nanoseconds. If the heating process in electrosurgical cutting was fast enough to generate these acoustic waves, it seems reasonable that the acoustic waves would aid in the cellular disruption or ablation process. Note that if tissue disruption is obtained by pressure increases minimal vaporization is required to achieve cutting. This may explain some of Oringer's electron micrographic observations of cut dental tissue (Chapter 2, Section 2.3), in which single cells were split with no observable damage to essential cell structures such as the nucleus. Acoustic waves, like the power density fields, dissipate within a very short distance of their origin in solid tissue due to viscoelastic dissipation.

When cutting is performed the scalpel electrode is not in mechanical contact with the tissue, but rather rides on a vapor film as it is moved through the tissue. If one attempts to move the scalpel too quickly, the excess drag of the tissue is felt and the cutting process is slowed. The separation between the scalpel and tissue allows the possibility of arc formation while cutting. Certainly, if an arc exists between the wire and the tissue, the current is much more confined than if the wire is immersed in the tissue with no arc. It is quite reasonable to expect, therefore, that a cutting loop or scalpel electrode is made effective by arc establishment. Arcs by their nature are highly localized in both space and time and consist of very short high current density discharges which satisfy all of the requirements for effective cutting.

The small cross-sectional area of the arc gives very high current densities which are so localized that the current field spreads out within an extremely short distance of the strike point. The arc is so small compared to the wire diameter that the place where it strikes the tissue may be thought of as approximately a point. A point strike means that the volumetric power density in the tissue drops roughly as the reciprocal of the fourth power of the radius rather than the square of the radius as in the wire conduction problem analyzed by Honig. This is because the electric field due to a point or spherical source depends on the reciprocal of the square of the radius. The E-field may be expressed in terms of the total arc current, under the assumption that a finite cylindrical arc impinges on tissue from non-conducting air. As shown in Fig. 4.7, the arc has been idealized to a finite cylindrical cross-section of small diameter compared to the wire loop

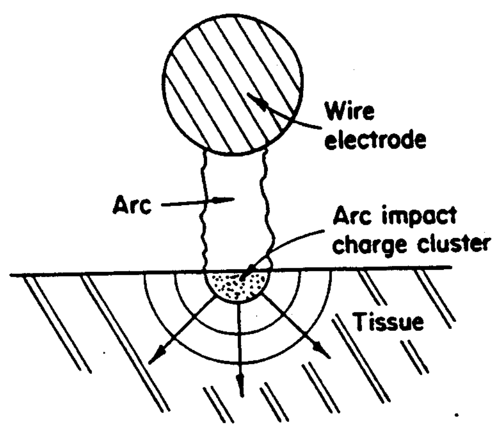

Fig. 4.7 Illustration of an idealized arc striking from a wire electrode to the tissue. A cylindrical cross-section is assumed for the arc which creates an imagined hemispherical space charge region when it impacts the tissue. The resulting electric and current density fields are equivalent to those of a point source.

electrode. The arc impinging on the idealized tissue is imagined to create an approximately hemispherical excess charge zone which is the origin of the tissue electric field. The hemispherical assumption is a convenient simplification which makes possible the calculation of the local power density. If one assumes instead that the excess charge zone is a circular surface charge, essentially the same power density is found within about two arc radii, but the calculation is much more difficult – it resembles the circular disk electrode which is discussed in Chapter 5. Assuming a hemisphere reduces the fields to those of an equivalent point charge:

$$\mathbf{E} = \frac{I}{2\pi\sigma r^2}\,\mathbf{a}_r = \frac{M}{r^2}\,\mathbf{a}_r \qquad (4.6)$$

Where E = electric field (V/m)
I = total current in the arc (A)
σ = medium conductivity (S/m)
r = radial distance in spherical coordinates from the point at which E is wanted to the center of the arc (m)
M = a convenient constant

The power density is then:

$$P = \frac{M^2}{\sigma r^4} \tag{4.7}$$

Figure 4.8 compares the power density profiles (as a function of distance from the active electrode) in the wire model with the hemispherical charge zone location in the arc model. The striking feature of the figure is the rate of

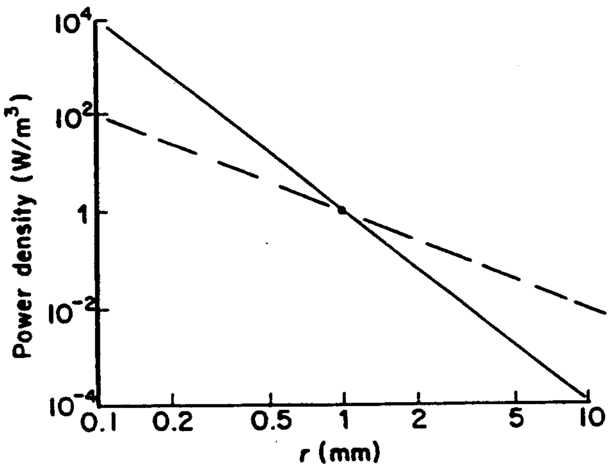

Fig. 4.8 Power density profiles for the cylindrical source of Fig. 4.6 (dashed line) and point source of Fig. 4.7 (solid line) both normalized for a power density of 1 W/m^3 at a radius of 1 mm.

increase of power density in the small arc case, and the corresponding rapid fall-off of the power density in deep tissues. Also note that the minimum radius in the small arc case is much less than the minimum radius in the line source case where it is limited to the wire radius.

The location of the arc stike point on the tissue is random and it probably wanders around the tissue surface (within limits), under the scalpel electrode. The very short duration of a single arc – less than one half-cycle of the wave used – virtually eliminates deep cell layer damage caused by heat transfer mechanisms during its conducting period. For the duration of a single arc all of the electrode current flows through that small conductive area. The line source model has current distributed over the entire electrode surface. Continuously applied currents in the line source model allow for

extent at both ends of the spectrum is, however, somewhat of a surprise.

In a series of experiments, the voltage and current spectra of cut and coagulate waveforms were measured for no arc at the tissue and when an arc was established at the scalpel electrode. All measurements were conducted at a current of 200 mA (r.m.s.). When an arc was established, an effort was made to obtain a particularly intense one in order to realize clearly identifiable arc effects. The intensity of the arc depends on the breakdown voltage, which in turn depends on the distance of the scalpel electrode from the tissue and on the concentration of residual ions from previous discharges, so its occurance and intensity are quite random. Nevertheless, the results obtained in the experiments are quite repeatable.

The first series of experiments was conducted on an isolated solid-state generator with a fundamental frequency of 500 kHz (Valleylab SSE2-K) for the cut waveform. The coagulate waveform had a 450 kHz fundamental, f_O, and a repeat frequency of 20 kHz. In Fig. 4.16 the time domain and frequency domain voltage signals of the cut waveform are shown when there was no surgical arc (Fig. 4.16(a)) and when an arc was established (Fig. 4.16(b)). The time domain voltage waveform is changed little by arc establishment, except in magnitude, and at constant current the equivalent impedance of the arc is about 1.1 kΩ. The arc components are much more prevalent in the current spectra (Fig. 4.17) and extend to high frequencies (>7 MHz) and low frequencies (<20 kHz). Note that in this figure the time domain current waveform is significantly distorted by arc establishment and is looking a little peaked. The point of breakdown is visible in the time domain current waveform. The shape change in the time domain (toward a triangular wave) gives a very strong third harmonic component, which can be seen in the frequency spectrum. Similar time and frequency domain data are shown in Fig. 4.18 for the coagulate voltage waveform. The effect on the time domain voltage signal is again minimal, but broad spectrum arc components can clearly be seen in the frequency domain. The current spectra for the same experiment, shown in Fig. 4.19, show a similar trend – much wider extent of arc spectral components and more distortion of the time domain waveform.

A second series of experiments was conducted on a Bovie AG generator which has a fundamental frequency of 2.3 MHz for the cut waveform and 500 kHz for the coagulate waveform with a repetition rate of 120 Hz. The time and frequency domain data of the cut waveform in Fig. 4.20 and 4.21 follow the same trend as the Valleylab device. The high frequency components are stronger in the current waveform, its distortion is similar, and the high frequency components extend to about 30 MHz, which is a little surprising. The arc equivalent impedance was about 930 Ω in this measurement. Measurements on the coagulate waveform (Fig. 4.22) showed no difference when an arc was established at the tissue because the coagulate waveform was produced with a spark gap generator.